Mitglied der Helmholtz-Gemeinschaft

Vergleich des Standes und Aussichten von Brennstoffzellenfahrzeugen mit Batteriefahrzeugen

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Institute of Electrochemical Process Engineering (IEK-3)

AKE-Frühjahrssitzung
Bad Honnef
16.04.2015
Vehicles
## Select Battery Electric Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Tesla 85D</th>
<th>e-Golf</th>
<th>BMW i3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor power</strong></td>
<td>315 kW (428 PS)</td>
<td>85 kW (115 PS)</td>
<td>125 kW (170 PS)</td>
</tr>
<tr>
<td><strong>Range (NEDC)</strong></td>
<td>502 km</td>
<td>190 km</td>
<td>190 km</td>
</tr>
<tr>
<td><strong>Consumption (NEDC)</strong></td>
<td>16.9 kWh/100km</td>
<td>12.7 kWh/100km</td>
<td>12.9 kWh/100km</td>
</tr>
<tr>
<td><strong>Battery capacity</strong></td>
<td>85 kWh</td>
<td>24.2 kWh</td>
<td>18.8 kWh</td>
</tr>
<tr>
<td><strong>Top speed</strong></td>
<td>250 km/h</td>
<td>140 km/h</td>
<td>150 km/h</td>
</tr>
<tr>
<td><strong>Acceleration 0-100 km/h</strong></td>
<td>4.6 s</td>
<td>10.4 s</td>
<td>7.2 s</td>
</tr>
<tr>
<td><strong>Base price</strong></td>
<td>85,900 €</td>
<td>34,900 €</td>
<td>34,950 €</td>
</tr>
</tbody>
</table>

Sources:
- [www.volkswagen.de/emobility](http://www.volkswagen.de/emobility)
First Fuel Cell Vehicles in Market Introduction Phase

1994: MB NECAR 1 (H₂)
1996: GM Electrovan (H₂, AFC)
1999: Honda FCX V1 (H₂)
2001: MB NECAR 5.2, methanol reformer
2001: GM Chevrolet S-10 gasoline reformer
2002: Honda FCX-V4: 1st FCV commercially certified *
2002: Cold start at -20°C (GM)
2006: HT-PEM (Volkswagen)
2006-2009: Small series for demonstration projects
   MB B-Class F-Cell
   GM HydroGen4
   Honda FCX Clarity
2012/13: Hyundai ix35 FCEV 1st manufact. plant
2015: Toyota Mirai 2nd series prod.

60s 70s 80s 1990s 2000s 2010s

Fuel cell APUs for passenger cars, trucks, train, ships & airplanes

Small series for demonstration projects

* First fuel-cell vehicle certified by the U.S. EPA and California Air Resources Board (CARB) for commercial use
MB: Mercedes-Benz; GM: General Motors
All cars with PEFC except GM Electrovan with AFC

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### Commercial FC Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Toyota Mirai</th>
<th>Hyundai iX35</th>
<th>Hyundai Tucson (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle type</strong></td>
<td>front-motor, front-wheel-drive, 4-pasenger, 4-door sedan, one-speed direct drive</td>
<td>Electric reducer FWD, 5-seater [planetary type mechanical variable speed transmission drive]</td>
<td>Compact SUV, 5-seater, single-speed transmission FWD</td>
</tr>
<tr>
<td><strong>Motor Power</strong></td>
<td>115 kW Synchronous AC</td>
<td>100 kW Induction motor</td>
<td>100 kW</td>
</tr>
<tr>
<td><strong>Torque</strong></td>
<td>335 Nm (247 lb-ft)</td>
<td>300 Nm (30.6 kgm)</td>
<td>221 lb-ft or Nm</td>
</tr>
<tr>
<td><strong>Fuel Cell Power</strong></td>
<td>144 kW</td>
<td>-</td>
<td>100 kW</td>
</tr>
<tr>
<td><strong>Range (NEDC)</strong></td>
<td>502 km</td>
<td>594 km (144 liter H₂ tank)</td>
<td>424 km (265 mi)</td>
</tr>
<tr>
<td><strong>Consumption (NEDC)</strong></td>
<td>5.8/5.0 l/100km eq. (56/58 MPGe)</td>
<td>0.8896 kg H₂/100km city 0.9868 H₂/100km highway</td>
<td>-</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td>NiMH</td>
<td>Lithium polymer 24 kW</td>
<td>Li-pol. 60 Ah, 24 kW, 0.95 kWh</td>
</tr>
<tr>
<td><strong>Top speed</strong></td>
<td>177 km/h</td>
<td>160 km/h</td>
<td>160 km/h</td>
</tr>
<tr>
<td><strong>Acceleration</strong></td>
<td>9 s 0-97 km/h (0-60 mph)</td>
<td>-</td>
<td>12.6 s 0-62 mph</td>
</tr>
<tr>
<td><strong>Curb weight</strong></td>
<td>1860 kg (4100 lb)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Base price</strong></td>
<td>58,395 US$</td>
<td>-</td>
<td>Lease: 2,999 down; 499 monthly @36 months (incl. fuel &amp; maintenance)</td>
</tr>
</tbody>
</table>

- [https://www.hyundaiusa.com/tucsonfuelcell/](https://www.hyundaiusa.com/tucsonfuelcell/)

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## Fuel Cell Systems

<table>
<thead>
<tr>
<th>OEM</th>
<th>Model</th>
<th>Temperatur [°C]</th>
<th>Pressure [bar]</th>
<th>Electrolyte</th>
<th>Bipolar Plate</th>
<th>P-density [kW/l]</th>
<th>Hydrogen tank pressure</th>
<th>H₂ consump. [kg/100km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daimler with Ford</td>
<td>F-CELL</td>
<td>~80</td>
<td>~2.0</td>
<td>perfluorated</td>
<td>graphitic</td>
<td>700</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>Hydrogen4</td>
<td></td>
<td></td>
<td></td>
<td>graphitic</td>
<td>700</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Honda</td>
<td>FCX Clarity</td>
<td>95</td>
<td>2.0</td>
<td>aromatic</td>
<td>metallic</td>
<td>1.9</td>
<td>350 (⇌700)</td>
<td>1.0</td>
</tr>
<tr>
<td>Hyundai</td>
<td>ix35 FCV</td>
<td>70</td>
<td>0.2</td>
<td>metallic</td>
<td></td>
<td>700</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Toyota with BMW</td>
<td>Mirai</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.1</td>
<td>700</td>
<td>1.0</td>
</tr>
</tbody>
</table>


Reasons, Scope and Timeline for Change
Modern CO₂ Level Rise is Unmatched in Human History

400 ppm Level: last sustainedly reached 14-20 million years ago, Middle Miocene, 5-10 °C warmer than today, no Arctic ice cap, sea level 25-40 m higher
DOI: 10.1126/science.1178296

Life Expectancy of a baby born today in DE:
100 years ↗ 2115

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Future Energy Solutions need to be Game Changers

Drivers

- Climate change
- Energy security
- Competitiveness
- Local emissions

Grand Challenges

- Renewable energy
- Electro-mobility
- Efficient central power plants
- Fossil cogeneration
- Storage
- Transmission
- Interconnect the energy sectors to leverage synergies

Goals

- 2 degrees climate goal requires ............... 50% ....by 2050 worldwide
- G8 goal ..................................................80% ....by 2050 w/r 1990
- Germany to reduce GHG emissions by ......80-95% by 2050 (w/o nuclear)
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### GHG Emissions Shares by Sector in Germany (2010)

**Emissions** | **Remedies (major vectors)**
---|---
Energy sector | 37% |
- Power generation | 30% | → 22.5 % Renewables |
Transport (90% petroleum-based) | 17% |
- Passenger vehicles | 11% | → 8.3 % Hydrogen / battery vehicles |
- Trucks, buses, trains, ships, airplanes | 6% | → 4.5 % Liquid fuel substitutes  
(biomass/CO₂-based; hydrogenation)
Residential | 11% |
- Residential heating | 11% | → 8.3 % Insulation, heat pumps etc.  
(electricity in power generation)
Industry, trade and commerce | 23% |
- Industry | 19% | → 9.5 % CO₂-capture from steel, cement, ammonia; hydrogen for CO₂-use |
- Trade and commerce | 4% | → 25 % already cleaned-up since 1990 |
Agriculture and forestry | 8% | 78.1% clean-up |
Others | 4% |
Total | 100% |

**Source:** Emission Trends for Germany since 1990, Trend Tables: Greenhouse Gas (GHG) Emissions in Equivalents, without CO₂ from Land Use, Land Use Change and Forestry, Umweltbundesamt 2011

Transport-related values: supplemented with Shell LKW Studie – Fakten, Trends und Perspektiven im Straßengüterverkehr bis 2030.
Timeline for CO$_2$-Reduction and the Implication of TRL Levels

- **2050**: 80% reduction goal fully achieved
- **2040**: start of market penetration
- **2030**: research finalized for 1st generation technology

**Development period**: unil 2040

**Research period**: until 2030

⇒ 15 years left for research => TRL 5 and higher

TRL 4 at least

This is not to say research at lower TRL levels is not useful, it will just not contribute to the 2050 goal
Renewable Power Generation
Excess Power is Inherent to Renewable Power Generation

Power Generation

Power Grid

Elektrolysis

H2-Storage

Gas Grid

H2-Storage

Power to Fuel

Power to Chem

Power to Gas (H2)

Power to Gas (CH4)

Households

Transportation

Industry

Institute of Electrochemical Process Engineering (IEK-3)
Development of Renewables According to Current German Policy

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak excess power*</td>
<td>GW_e</td>
<td>22</td>
<td>55</td>
<td>90</td>
</tr>
<tr>
<td>Excess energy*</td>
<td>TWh_e</td>
<td>2,5</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Minimum storage size**</td>
<td>TWh</td>
<td>0,9</td>
<td>6</td>
<td>12</td>
</tr>
</tbody>
</table>
Overcapacity in Power is Inherent for Full Renewable Energy Supply

\[
\text{renewable power needed} = \text{capacity factor} \times \text{average power demand}
\]

- Averaged power demand for Germany: \( \sim 60 \text{GW} \)
- Capacity factor for full renewable power supply:
  - Onshore wind \( \rightarrow 4.4 \)
  - Offshore wind \( \rightarrow 2.2 \)

\[\text{\@ no losses for reconversion considered}\]

\( \rightarrow \) Installed renewable power exceeds power demand on a regular basis
Why are There so Many Contradictory Assessments on Storage?

The necessity of using chemical energy storage depends on:

• The time-line

  The shorter the time-line the less storage will be needed. The need of storage at an earlier time might not be in line with the lead-time needed for furnishing later storage requirements.

• The energy sectors included

  If only the power sector gets considered, storage will be necessary much later compared to scenarios which look into a comprehensive CO2 clean-up of whole energy sector, including transportation and industry. Households might not have that a strong impact on the storage scenarios.

  Scenarios considering just the power sector at 2030 consistently report that no storage will be needed. That does not take into account that additional electrical energy will be needed for transportation and industry, currently fueled by fossils.

• The level of penetration of renewable energy

  If only intermediate levels of RE penetration is envisaged / imagined there is little need for storage. Yet, that is not in line with political goals and societal requirements.

• Whether the political goals (of the German Energy Strategy) are accepted / taken seriously

  The assessments depend on the assumptions to an unusual extent
Vehicles in Use
Electrification of Cars Increases

- Re-orientation in the energy sector is related to energy-strategic targets: energy imports, environmental impact, economic competitiveness
- Transportation: i.a. new powertrains and fuels for road transport
  - Advanced and increasingly hybridized powertrains with internal combustion engines
  - Plug-in hybrids with internal combustion engines
  - Zero emission electric powertrains with battery
  - Zero emission electric powertrains with fuel cells

**Level of electrification**

- *Electric car with fuel cells*
- *Electric car with batteries*

**Today's ICE**
- Generator
- SLI battery

**Micro-Hybrid**
- 2-3 kW<sub>e</sub>
- Stop-Start
- Recup. braking

**Mild-Hybrid**
- 10-15 kW<sub>e</sub>
- Stop-Start
- Recup. braking
- Torque assist

**Full-Hybrid (Plug-in)**
- >15 kW<sub>e</sub>
- Stop-Start
- Recup. braking
- Torque assist
- Electric driving

ICE: internal combustion engine
SLI: starting, lighting and ignition
What are New Components of BEV and FCV?

Powertrain
- Electric motor/generator and gearbox
- High-voltage power distribution
- Electric braking
- Power electronics and operational strategy

Comfort and Safety
- Electric steering
- Air conditioning (electrically powered, highly-efficient)

FCV only
- Fuel cells system and gas storage
- Hybrid battery including battery management system

BEV only
- Traction battery including battery management system
Simulation-Based Fuel Economy Assessments

- Quantification of fuel use in drive cycles using:
  - Quasi-stationary or dynamic simulation models with physical or map-based component description
  - Examples: AVL CRUISE (AU), ADVISOR (USA), PSAT Engine/Autonomie (USA)
  - At IEK-3: own simulation model development based on Matlab/Simulink®

- Load profiles:
  - mechanical: drive cycles for covering different user profiles, e.g.
    - Electric: base load and additional consumers of the 14 V onboard grid
    - Thermal: cabin conditioning (heating and cooling)
Drive Cycle has Great Impact on Mechanical Energy Requirement of Cars

- The figure shows positive (acceleration) and negative (braking) energy requirements of a compact car according to [1]
- Vehicle weight: 1251 kg; frontal area: 2.1 m²; air drag coefficient: 0.32


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Auxiliary Power Particularly Relevant at Low Average Speed

Fuel consumption of vehicles is defined by

- time dependent velocity, e.g. of drive cycle for passenger car type approval
- auxiliary power requirement of electric onboard grid, heating and cooling

**Additional fuel use at 1kW_e auxiliary power**

**Values for the European Drive Cycle (MVEG)**

**Passenger car with:**

<table>
<thead>
<tr>
<th>ICE</th>
<th>Fuel cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_{\text{diff,m}} = 0.4; \ \eta_G = 0.6)</td>
<td>(\eta_e = 0.6)</td>
</tr>
<tr>
<td>(\eta_e = \eta_{\text{diff,m}} \times \eta_G = 0.24)</td>
<td></td>
</tr>
<tr>
<td>0.7 – 2.5 l_{\text{ge}} (100km)^{-1}</td>
<td>0.3 – 1.0 l_{\text{ge}} (100km)^{-1}</td>
</tr>
</tbody>
</table>

**Indices:**
- diff: differential; e: electric; G: generator
- m: mechanical; SBS: electricity provision; l_{\text{ge}}: liters of gasoline equivalent; KS: fuel


Values related to MVEG drive cycle (EU regulation 80/1268/EWG [1])
## Assumptions for Well-to-Wheel Data

<table>
<thead>
<tr>
<th></th>
<th>Primary energy</th>
<th>Fuel production and distribution</th>
<th>Fuel use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BEV</strong></td>
<td>German Electricity mix: 36 % efficiency, 559 gCO₂/kWhₑ</td>
<td>-</td>
<td>13 kWhₑ/100km</td>
</tr>
<tr>
<td>Standard case</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BEV</strong></td>
<td>Renewable Electricity, per definition 100 % primary energy; natural gas power plants for pos. residual energy, 62 gCO₂/kWhₑ</td>
<td>-</td>
<td>13 kWhₑ/100km</td>
</tr>
<tr>
<td><strong>Renewable</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FCV</strong></td>
<td>Natural gas provision: 85 % efficiency</td>
<td>Steam reforming of natural gas; pipeline distribution; 880 bar at dispenser</td>
<td>0.8 kgH₂/100km</td>
</tr>
<tr>
<td>Standard case</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FCV</strong></td>
<td>Renewable Electricity not usable in the grid, per definition 100 % primary energy</td>
<td>Electrolysis with 70 % efficiency; pipeline distribution; 880 bar at dispenser</td>
<td>0.8 kgH₂/100km</td>
</tr>
<tr>
<td>Renewable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


GHG: Greenhouse gas emissions; ICV: Internal combustion engine vehicle; BEV: Battery vehicle; FCV: Fuel cell vehicle
**Well-to-Wheel: Energy and GHG comparison** *(Reference Case)*

<table>
<thead>
<tr>
<th></th>
<th>Fuel provision</th>
<th>Fuel use</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ICV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MJ/100km</td>
<td>31</td>
<td>174</td>
<td>205</td>
</tr>
<tr>
<td><strong>FCV</strong></td>
<td></td>
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</tr>
<tr>
<td>MJ/100km</td>
<td>77</td>
<td>95</td>
<td>173</td>
</tr>
<tr>
<td><strong>BEV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MJ/100km</td>
<td>64</td>
<td>49</td>
<td>113</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Fuel provision</th>
<th>Fuel use</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ICV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/km</td>
<td>24</td>
<td>128</td>
<td>152</td>
</tr>
<tr>
<td><strong>FCV</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>g/km</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>BEV</strong></td>
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<tr>
<td>g/km</td>
<td>75</td>
<td>0</td>
<td>75</td>
</tr>
</tbody>
</table>


GHG: Greenhouse gas emissions; ICV: Internal combustion engine vehicle; BEV: Battery vehicle; FCV: Fuel cell vehicle

Institute of Electrochemical Process Engineering (IEK-3)
<table>
<thead>
<tr>
<th></th>
<th>ICV</th>
<th></th>
<th>FCV</th>
<th></th>
<th>BEV</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>MJ/100km</td>
<td>Fuel use</td>
<td>Total</td>
<td>Fuel use</td>
<td>Total</td>
<td>Fuel use</td>
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<tr>
<td>Energy</td>
<td>Fuel provision</td>
<td>28</td>
<td>155</td>
<td>56</td>
<td>13</td>
<td>13</td>
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<tr>
<td></td>
<td>Fuel use</td>
<td></td>
<td>182</td>
<td></td>
<td>74</td>
<td></td>
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<tr>
<td></td>
<td>Total</td>
<td></td>
<td>131</td>
<td></td>
<td>131</td>
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<tr>
<td></td>
<td>Fuel provision</td>
<td></td>
<td></td>
<td>Fuel use</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>THG emissions</td>
<td>Fuel provision</td>
<td>21</td>
<td>113</td>
<td>0</td>
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<tr>
<td></td>
<td>Fuel use</td>
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<td>135</td>
<td></td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>135</td>
<td></td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel provision</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel use</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>


GHG: Greenhouse gas emissions; ICV: Internal combustion engine vehicle; BEV: Battery vehicle; FCV: Fuel cell vehicle

Institute of Electrochemical Process Engineering (IEK-3)
Well-to-Wheel: Primary Energy Use and GHG Emissions (Reference Case)


-> scenario „Standard“, values for all cycles and for all onboard grid load cases.

g e: gasoline equivalent; GH G: greenhouse gas; mix: electricity mix for Germany (2013); nat. gas: natural gas;
Well-to-Wheel: Primary Energy Use and GHG Emissions
(Renewable Energy Case)


-> scenario „Zukunft“, values for all cycles and for all onboard grid load cases.

g: gasoline equivalent; GHG: greenhouse gas; mix: electricity mix for Germany (2013); nat. gas: natural gas;
Fuel Tax Discussion

Fuel tax in Germany [ct/l]: 65.45 (gasoline), 47.04 (diesel)

**Case 1:** tax is constant on an energy basis

Average for energy equivalent: **53.8 ct/l**

**Case 2:** tax revenue is constant

Average for distance equivalent: **3.14 ct/km**

---

1) Fuel tax average of gasoline and diesel
2) Assuming constant passenger kilometers and vehicle occupation
3) 6.0 l/100 km, gasoline car; 5.0 l/100km diesel car

---

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Hydrogen Refueling Stations

- Investment costs for large scale H\textsubscript{2} refueling stations (capacity of 1500 kg\textsubscript{H2}/day) are predicted to drop to < 2 million Euro per station\textsuperscript{1)}
- Linde set up production line for 50 H\textsubscript{2} refueling stations per year in Vienna, Austria → Reduction of investment costs from 1.5 to 1 million Euro per refilling station (smaller scale)\textsuperscript{5)}

- Total costs and cost distribution vary drastically in literature according to station size, type of compressor, location and assumptions
- Main cost drivers are compressors and high-pressure storage → 50-75 % of total investment costs

\textsuperscript{1)} M. Wietschel, U. Bünger: Vergleich von Strom und Wasserstoff als CO\textsubscript{2}-freie Endenergieträger, 2010
\textsuperscript{2)} H2-Roadmap: AP1 “Prinzipielle Anforderungen an die Infrastruktur”, DWV, 2003
\textsuperscript{3)} B. Gim, W.L. Yoon: Analysis of the economy of scale and estimation of future hydrogen production costs at on-site hydrogen refueling stations in Korea, IJHE, 2012
\textsuperscript{4)} J.X. Weinert et al.: Hydrogen refueling station costs in Shanghai, IJHE, 2007
\textsuperscript{5)} http://www.hzwei.info/blog/2014/10/08/linde-startet-serienproduktion-von-h2-tankstellen/
Refueling and Charge Time for 100 km Operational Range

Assumptions:
- Gasoline (l/min): 50
- Hydrogen (kg/100km): 1
- Electric Power (kW): 3 | 10 | 30 | 120*

Fuel use [1]:
- 5.3 (4.8) l/100 km (Gasoline-ICE)
- 0.84 (0.65) kg/100km (FCV)
- 14 (11) kWh/100km (BEV)


3 kW: wall outlet | 10 kW: high-power wall outlet | 30 kW: public charging station | 120 kW: Tesla Supercharger
Alternative Drive Trains for Trucks

Data of a conventional 40 t trailer truck*:
- Engine Power: 350 kW
- Mean efficiency of diesel engine (Euro VI): 43.5 %
- Diesel consumption (Long Haul Cycle): 34.5 l_Diesel/100km (12.4 MJ/km)
- Tank volume: 800 l
- Range: 2300 km

Replacement of conventional diesel engine by battery or fuel cell driven electric motor:

**Fuel cell driven electric power train:**
- Mean efficiency of fuel cell: 60 %
- Hydrogen consumption (Long Haul Cycle): \( \rightarrow 7.5 \text{ kg}_\text{H}_2/100\text{km} \) (9.0 MJ/km)
- Required hydrogen tank (for same range): \( \rightarrow 172 \text{ kg}_\text{H}_2 \)
- Required hydrogen tank volume (0.83 kWh/l) and mass (1.7 kWh/kg): 6.9 m³ and 3.4 t

**Battery driven electric power train:**
- Mean efficiency of battery: 90 %
- Electricity consumption (Long Haul Cycle): \( \rightarrow 166 \text{ kWh}_\text{el}/100\text{km} \) (6.0 MJ/km)
- Required battery capacity (for same range): \( \rightarrow 3829 \text{ kWh} \)
- Required battery volume (300 Wh/l) and mass (150 Wh/kg): 12.7 m³ and 25.5 t

→ Low energy density of batteries and compressed hydrogen make use in heavy transport unlikely

*Umweltbundesamt: Zukünftige Maßnahmen zur Kraftstoffeinsparung und Treibhausgasminderung bei schweren Nutzfahrzeugen, 2015

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Cruising Range Depends on Drive Cycle and Auxiliary Power

Operational range increase or limitation for
- Internal combustion engine vehicles (ICV)
- Fuel Cell Vehicles
- Battery vehicles

Definitions according to [1]
- Compact car
- Scenario „Zukunft“

- All 25 drive cycles
- All onboard load cases
- Maximum and minimum fuel consumptions have been selected
- Nominal range according to fuel storage:
  - 50 l for ICV
  - 5 kg H2 for FCV
  - 24 kWh for BEV

In extreme cases (low cycle speed and high auxiliary power) operational range can be reduced by up to 60 %
Hydrogen Generation, Storage and Transmission
Options for Water Electrolysis

### Alkaline electrolysis
- Mature technology
- <3.6 MW stacks
- Plants <156 MW
- Ni catalysts
- 750 €/kW - 1000 €/kW

### PEM - electrolysis
- Development stage
- < 1 MW in development
- Pt and Ir as catalysts
- Simple plant design
- €1500@ 2015
- € 500@ 2030 (FZJ)

### Solid Oxide Electrolysis
- Laboratory stage
- Very high efficiency
- Brittle ceramics
- Hence, slow scale-up
- Just cost estimations
Decouple Power and Energy for Long-term Storage

Assumption: storage may add about the same price tag to the energy delivered, be it
- Short-term storage, or
- Long-term storage

<table>
<thead>
<tr>
<th></th>
<th>Storage cycles / a</th>
<th>Relative allowable invest / kWh*</th>
<th>Energy required</th>
<th>Energy specific investment cost</th>
<th>Power required</th>
<th>Additional cost for conversion units (electrolyzer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>100 - 1000</td>
<td>100%</td>
<td>some GWh</td>
<td>Batteries 100-200</td>
<td>some 10GW</td>
<td>none</td>
</tr>
<tr>
<td>Long-term</td>
<td>1 - 10</td>
<td>1%</td>
<td>some 1000 GWh</td>
<td>Salt cavern &lt; 1</td>
<td>some 10GW</td>
<td>500 €/kW</td>
</tr>
</tbody>
</table>

Uncoupling Power and Energy

Batteries: Power and energy scale linearly with unit size
Hydrogen: Power scales less than energy, this makes storage affordable

Electrolyzers
Gas caverns: allow for quick discharge ⇒ serve dynamic requirements

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### Geologic Gas Storage Facilities

<table>
<thead>
<tr>
<th></th>
<th>Depleted oil / gas fields</th>
<th>Aquifers</th>
<th>Salt caverns</th>
<th>Rock caverns / abandoned mines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working volume [scm]</td>
<td>$10^{10}$</td>
<td>$10^8$</td>
<td>$10^7$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Cushion gas</td>
<td>50 %</td>
<td>up to 80 %</td>
<td>20 - 30 %</td>
<td>20 - 30 %</td>
</tr>
<tr>
<td>Gas quality</td>
<td>reaction and contamination with present gases, microorganism and minerals</td>
<td></td>
<td>saturation with water vapor</td>
<td></td>
</tr>
<tr>
<td>Annual cycling cap.</td>
<td>only seasonal</td>
<td></td>
<td>seasonal &amp; frequent</td>
<td></td>
</tr>
</tbody>
</table>
Spatial Requirements for Transmission

Width of protective strips

70 m  
57 m  
48 m  
10 m


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## Power Line and Gas Pipelines Compared

<table>
<thead>
<tr>
<th></th>
<th>380 kV overhead line</th>
<th>Natural gas pipeline</th>
<th>Hydrogen gas pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>4 x 564/72 double circuit</td>
<td>DN 1000</td>
<td>$\text{p}_{\text{in}} = 90 \text{ bar}$</td>
</tr>
<tr>
<td>Energy transport capacity</td>
<td>1.2 GW$_{\text{el}}$</td>
<td>16 GW$_{\text{th}}$</td>
<td>12 GW$_{\text{th}}$</td>
</tr>
<tr>
<td>Investment cost in M€/km</td>
<td>1 - 1.5</td>
<td>1 - 2</td>
<td>1.2 - 3</td>
</tr>
</tbody>
</table>
Principle of a Renewable Energy Scenario with Hydrogen
Hydrogen as an Enabler for Renewable Energy

262 GW
(onshore, offshore & PV peak simultaneously)

84 GW
Electrolysis

80 GW
Grid Load

Curtailment regime

Electrolysis regime

Fill power gaps w/ NG via CC & GT

Power regime

37% of power curtailment sacrifices 2% of energy *

* modeled for DE based on inflated input of renewables w/ weather data of 2010
Cost of Infrastructure
Overview on Cost
for a Renewable Hydrogen Infrastructure for Transportation

Additional gas and combined cycle power plants

Electrolyzers (84 GW) 24

Rock salt caverns 150 x 750,000 scm 4,5

Pipeline grid (43-59,000 km) 19-25

Fueling stations (9,800) 20

Investment in bn €
# Cost Estimation of Battery Charging Infrastructure for Vehicles in DE

<table>
<thead>
<tr>
<th></th>
<th>1 Million BEV</th>
<th>30 Million BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of private garages</td>
<td>100%</td>
<td>37% ¹)</td>
</tr>
<tr>
<td>Public charging stations per vehicle</td>
<td>0.25–0.5</td>
<td>0.7–1.4 (McKinsey: 1.4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Number Million units</th>
<th>Cost bn €</th>
<th>Number Million units</th>
<th>Cost bn €</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private charging (garage), 1,000 € each</td>
<td>1,0</td>
<td>1,0</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Public charging stations, 6,500 € ²) each @ 40kW</td>
<td>0.25–0.50</td>
<td>1.6–3.3</td>
<td>21–42</td>
<td>136–273</td>
</tr>
<tr>
<td>Grid extension, 700 € each</td>
<td>negligible</td>
<td>-</td>
<td>32–53</td>
<td>22–37</td>
</tr>
<tr>
<td><strong>Total in bn €</strong></td>
<td><strong>2.6–4.3</strong></td>
<td></td>
<td><strong>169–321</strong></td>
<td></td>
</tr>
</tbody>
</table>


Information used: 63% of households in DE (39.1 mn @ 2009) dispose of a garage / parking space; thereof 61% are used by the owner.

²) Data from: Zweiter Bericht der Nationalen Plattform Elektromobilität. Nationale Plattform Elektromobilität (NPE), Berlin, 2011;

Information used: cost for charging station, metering and automated settlement, installation of charging station, connection to electric distribution grid, designation of e-parking space, cost for right of dedicated use (average values, respectively)
CAPEX via depreciation of investment plus interest

- 10 a for electrolysers and other production devices
- 40 a for transmission grid
- 20 a for distribution grid
- Interest rate 8 % p.a.

Other Assumptions:

- 5.4 million t_H2/a from renewable power via electrolysis
- Electrolysis: \( \eta = 70\%_{\text{LHV}} \); 84 GW; investment cost 500 €/kW
- Methanation: \( \eta = 80\%_{\text{LHV}} \)
- Grid fee for power transmission: 1.4 ct/kWh_e [1]

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Conclusions

• A fully renewable energy supply entails overcapacity in installed power and hence “excess power”
• 80% of CO₂ reduction requires interconnection of the energy sectors
  • Battery vehicles
  • Hydrogen vehicles
  • Hydrogenation steps in liquid fuel production from biomass and CO₂
• Conversion of excess power to hydrogen and storage thereof is feasible on the scale needed (TWh)
• Over long distances mass transportation of gas is more effective than that of electricity
• Battery vehicles are being introduced to the mass market
• cell vehicles are being introduced to the market by asian automakers
• Hydrogen as an automotive fuel is cost effective other than feed-in to the gas grid or reconversion to electricity
Institute of Electrochemical Process Engineering (IEK-3)

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